First Observation of CP Violation in B[over ¯]^{0}→D_{CP}^{(*)}h^{0} Decays by a Combined Time-Dependent Analysis of BABAR and Belle Data

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We report a measurement of the time-dependent CP asymmetry of $\overline{B}^0 \to D^{(*)}_{CP} h^0$ decays, where the light neutral hadron h^0 is a π^0, η or ω meson, and the neutral D meson is reconstructed in the CP eigenstates K^+K^-, $K^0_S\pi^0$ or $K^0_S\omega$. The measurement is performed combining the final data samples collected at the $\Upsilon(4S)$ resonance by the *BABAR* and Belle experiments at the asymmetric-energy B factories PEP-II at SLAC and KEKB at KEK, respectively. The data samples contain $(471\pm3)\times10^6$ $B\overline{B}$ pairs recorded by the *BABAR* detector and $(772\pm11)\times10^6$ $B\overline{B}$ pairs recorded by the Belle detector. We measure the *CP* asymmetry parameters $-\eta_f\mathcal{S} = +0.66\pm0.10\,(\text{stat.})\pm0.06\,(\text{syst.})$ and $\mathcal{C} = -0.02\pm0.07\,(\text{stat.})\pm0.03\,(\text{syst.})$. These results correspond to the first observation of *CP* violation in $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays. The hypothesis of no mixing-induced *CP* violation is excluded in these decays at the level of 5.4 standard deviations.

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In the standard model (SM) of electroweak interactions, *CP* violation arises from an irreducible complex phase in the three-family Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [1]. The *BABAR* and Belle experiments have established *CP* violating effects in the B meson system [2–5]. Both experiments use their measurements of the mixing-induced *CP* violation in $b \to c\bar{c}s$ transitions [6, 7] to determine precisely the parameter $\sin(2\beta) \equiv \sin(2\phi_1)$ [*BABAR* uses β and Belle uses ϕ_1, hereinafter β is used]. The angle β is defined as $\arg\left[-V_{cd}V^*_{cb}/V_{td}V^*_{tb}\right]$, where V_{ij} is the CKM matrix element of quarks i, j.

A complementary and theoretically clean approach to access β is provided by $\overline{B}^0 \to D^{(*)0}h^0$ decays, where $h^0 \in \{\pi^0, \eta, \omega\}$ denotes a light neutral hadron. These decays are dominated by CKM-favored $b \to c\bar{u}d$ tree amplitudes. CKM-disfavored $b \to u\bar{c}d$ amplitudes carrying different weak phases contribute also to the decays, but are suppressed by $V_{ub}V^*_{cd}/V_{cb}V^*_{ud} \approx 0.02$ relative to the leading amplitudes. An interference between the decay amplitudes without and with B^0-$\overline{B}^0$ mixing emerges if the neutral D meson decays to a *CP* eigenstate D_{CP}. Neglecting the suppressed amplitudes, the time evolution of $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays is governed by β [8]. Because only tree-level amplitudes contribute to $\overline{B}^0 \to D^{(*)0}h^0$ decays, these decays are not sensitive to most models of physics beyond the standard model (BSM). However, the measurement of the time-dependent *CP* violation enables testing of the measurements of $b \to c\bar{c}s$ transitions [6, 7] and provides a SM reference for the BSM searches in the mixing-induced *CP* violation of $b \to s$ penguin-mediated B meson decays [9–12]. Any sizable deviation in the *CP* asymmetry of $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays from processes involving $b \to c\bar{c}s$ or penguin-mediated $b \to s$ transitions would point to BSM. Such deviations could for example be caused by unobserved heavy particles contributing to loop diagrams in $b \to c\bar{c}s$ or $b \to s$ penguin transitions [13].

An experimental difficulty in the use of $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays arises from low B and D meson branching fractions [$\mathcal{O}(10^{-4})$ and $\mathcal{O}(\leq 10^{-2})$, respectively] and low reconstruction efficiencies. Previous measurements performed separately by the *BABAR* and Belle collaborations were not able to establish *CP* violation in these or related decays [14–16].

In this Letter, we present a measurement of the time-dependent *CP* violation in $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays. For the first time, we combine the large final data samples collected by the *BABAR* and Belle experiments. This new approach enables time-dependent *CP* violation measurements in the neutral B meson system with unprecedented sensitivity.

The time-dependent rate of a neutral B meson decaying to a *CP* eigenstate is given by

$$g(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 + q[\mathcal{S}\sin(\Delta m_d\Delta t) - \mathcal{C}\cos(\Delta m_d\Delta t)]\}, \quad (1)$$

where $q = +1\,(-1)$ represents the b-flavor content when the accompanying B meson is tagged as a B^0 ($\overline{B}^0$) and Δt denotes the proper time interval between the decays of the two B mesons produced in an $\Upsilon(4S)$ decay. The neutral B meson lifetime is represented by τ_{B^0}, and the B^0-$\overline{B}^0$ mixing frequency by Δm_d. Neglecting the CKM-disfavored decay amplitudes in $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays, the SM predicts $\mathcal{S} = -\eta_f\sin(2\beta)$ and $\mathcal{C} = 0$, where η_f is the *CP* eigenvalue of the final state, and $\mathcal{S}$ and $\mathcal{C}$, respectively, quantify mixing-induced and direct *CP* violation [17].

This analysis is based on data samples collected at the $\Upsilon(4S)$ resonance containing $(471\pm3)\times10^6$ $B\overline{B}$ pairs recorded with the *BABAR* detector at the PEP-II asymmetric-energy e^+e^- (3.1 on 9 GeV) collider [18] and $(772\pm11)\times10^6$ $B\overline{B}$ pairs recorded with the Belle detector at the KEKB asymmetric-energy e^+e^- (3.5 on 8 GeV) collider [19]. At *BABAR* (Belle) the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.560$ (0.425), allowing the measurement of Δt from the displacement of the decay vertices of the two B mesons. The *BABAR* and Belle detectors are described in Refs. [20, 21].

Reconstructed tracks of charged particles are considered as kaon and pion candidates. Kaons are identified using the particle identification techniques described in Refs. [20, 21]. Photons are reconstructed from energy deposits in the electromagnetic calorimeters, and the energy of photon candidates is required to be at least 30 MeV. Combinations of two photons are considered as π^0 meson candidates if the reconstructed invariant mass is between 115 and 150 MeV/c^2. Candidate η mesons are reconstructed in the decay modes $\eta \to \gamma\gamma$ and $\pi^+\pi^-\pi^0$. The invariant mass is required to be within 20 MeV/c^2 of the nominal mass [22] for $\eta \to \gamma\gamma$ candidates, and within

10 MeV/c^2 for $\eta \to \pi^+\pi^-\pi^0$ candidates. For each photon in the $\eta \to \gamma\gamma$ decay mode a minimal energy of 50 MeV is required.

For ω mesons the decay mode $\omega \to \pi^+\pi^-\pi^0$ is reconstructed with invariant mass required to be within 15 MeV/c^2 of the nominal mass [22]. Neutral kaons are reconstructed in the decay mode $K^0_S \to \pi^+\pi^-$, with invariant mass required to be within 15 MeV/c^2 of the nominal mass [22]. The requirements exploiting the K^0_S decay vertex displacement from the interaction point (IP) described in Refs. [15, 23] are applied. Neutral D mesons are reconstructed in the decay modes to CP eigenstates $D_{CP} \to K^+K^-$, $K^0_S\pi^0$ and $K^0_S\omega$. The invariant mass is required to be within 12 MeV/c^2 of the nominal mass [22] for $D_{CP} \to K^+K^-$ candidates, within 25 MeV/c^2 for $D_{CP} \to K^0_S\pi^0$ candidates, and within 20 MeV/c^2 for $D_{CP} \to K^0_S\omega$ candidates. We reconstruct D^{*0} mesons in the decay mode $D^{*0} \to D^0\pi^0$, and the invariant mass must be within 3 MeV/c^2 of the nominal mass [22].

Neutral B mesons are reconstructed in the CP-even ($\eta_f = +1$) final states $\overline{B}^0 \to D_{CP}\pi^0$ and $D_{CP}\eta$ (with $D_{CP} \to K^0_S\pi^0$, $K^0_S\omega$), $\overline{B}^0 \to D_{CP}\omega$ (with $D_{CP} \to K^0_S\pi^0$), $\overline{B}^0 \to D^*_{CP}\pi^0$ and $D^*_{CP}\eta$ (with $D_{CP} \to K^+K^-$), and in the CP-odd ($\eta_f = -1$) final states $\overline{B}^0 \to D_{CP}\pi^0$, $D_{CP}\eta$, $D_{CP}\omega$ (with $D_{CP} \to K^+K^-$), and $\overline{B}^0 \to D^*_{CP}\pi^0$ and $D^*_{CP}\eta$ (with $D_{CP} \to K^0_S\pi^0$) [24].

Neutral B mesons are selected by the beam-energy-constrained mass $M_{\rm bc} \equiv m_{\rm ES} = \sqrt{(E^*_{\rm beam}/c^2)^2 - (p^*_B/c)^2}$ [*BABAR* uses $m_{\rm ES}$ and Belle uses $M_{\rm bc}$, hereinafter $M_{\rm bc}$ is used] and by the energy difference $\Delta E = E^*_B - E^*_{\rm beam}$, where $E^*_{\rm beam}$ denotes the energy of the beam, and p^*_B and E^*_B are the momentum and energy of the B meson candidates, evaluated in the e^+e^- center-of-mass (c.m.) frame. The selected regions are 5.2 GeV/c^2 $< M_{\rm bc} <$ 5.3 GeV/c^2 and $-100\,\text{MeV} < \Delta E < 100\,\text{MeV}$, except for $\overline{B}^0 \to D^{(*)}_{CP}\pi^0$ decays, where $-75\,\text{MeV} < \Delta E < 100\,\text{MeV}$ is required to exclude tails from partially reconstructed $B^- \to D^{(*)0}\rho^-$ decays peaking at $\Delta E \approx -250\,\text{MeV}$.

In $\overline{B}^0 \to D^0\omega$ and in $D^0 \to K^0_S\omega$ decays, the ω vector mesons are polarized. The angular distribution of $\omega \to \pi^+\pi^-\pi^0$ decays is exploited to discriminate against background. The quantity $\cos\theta_N$ is defined as the cosine of the angle between the neutral B meson direction and the normal to the $\pi^+\pi^-\pi^0$ plane in the ω meson rest frame. A requirement of $|\cos\theta_N| > 0.3$ is applied.

After applying the above selection requirements, the average multiplicity of reconstructed $\overline{B}^0 \to D^{(*)}_{CP}h^0$ candidates in an event is 1.3. In case of multiple B meson candidates in an event, one candidate is selected using a criterion based on the deviations of the reconstructed $D^{(*)}$ and h^0 meson masses from the nominal values. The probability for this method to select the correct signal is 82% (81%) for *BABAR* (Belle).

In $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays, the dominant source of background originates from $e^+e^- \to q\bar{q}$ ($q \in \{u, d, s, c\}$) continuum events. This background is suppressed by using neural network (NN) multivariate classifiers that combine information characterizing the shape of an event [25]. The observables included in the NNs are the ratio R_2 of the second to the zeroth order Fox-Wolfram moment, a combination of 16 modified Fox-Wolfram moments [26], the sphericity of the event [27], and $\cos\theta^*_B$, where θ^*_B is the angle between the direction of the reconstructed B meson and the beam direction in the c.m. frame. The NN selection reduces the background by 89.3% (91.8%) and has a signal efficiency of 75.5% (74.3%) for *BABAR* (Belle).

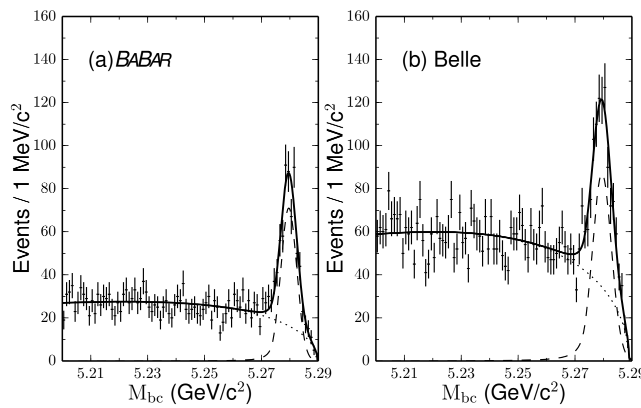

FIG. 1. The $M_{\rm bc}$ distributions (data points with error bars) and fit projections (solid line) of $\overline{B}^0 \to D^{(*)}_{CP}h^0$ decays for (a) *BABAR* and (b) Belle. The dashed (dotted) lines represent projections of the signal (background) fit components.

The signal yields are determined by unbinned maximum likelihood fits to the $M_{\rm bc}$ distributions. In the fits, the signal component is parametrized by a Crystal Ball function [28] and the background component is modeled by an ARGUS function [29]. The experimental $M_{\rm bc}$ distributions and fit projections are shown in Fig. 1. The signal yields are summarized in Table I.

TABLE I. Summary of $\overline{B}^0 \to D^{(*)}_{CP}h^0$ signal yields.

Decay mode	*BABAR*	Belle
$\overline{B}^0 \to D_{CP}\pi^0$	241 ± 22	345 ± 25
$\overline{B}^0 \to D_{CP}\eta$	106 ± 14	148 ± 18
$\overline{B}^0 \to D_{CP}\omega$	66 ± 10	151 ± 17
$\overline{B}^0 \to D^*_{CP}\pi^0$	72 ± 12	80 ± 14
$\overline{B}^0 \to D^*_{CP}\eta$	39 ± 8	39 ± 10
$\overline{B}^0 \to D^{(*)}_{CP}h^0$ total	508 ± 31	757 ± 44

The time-dependent CP violation measurement is performed using established *BABAR* and Belle techniques for the vertex reconstruction, the flavor-tagging, and the modeling of Δt resolution effects (see Refs. [6, 7, 30–33]) and is briefly summarized below. The proper time interval Δt is given as $\frac{\Delta z}{c\beta\gamma}$, where Δz is the distance between the decay vertices of the signal B meson and of the accompanying B meson. The $\bar{B}^0 \to D_{CP}^{(*)} h^0$ signal decay vertex is reconstructed by a kinematic fit including information about the IP position. For Belle, an iterative hierarchical vertex reconstruction algorithm following a bottom-up approach starting with the final state particles is applied, while for BABAR the vertex reconstruction includes simultaneously the complete B meson decay tree including all secondary decays. In the kinematic fits, the invariant masses of π^0, η, ω, and D_{CP} candidates are constrained to their nominal values [22]. The decay vertex and the b-flavor content of the accompanying B meson are estimated from reconstructed decay products not assigned to the signal B meson. The b-flavor content is inferred by flavor-tagging procedures described in Refs. [6, 32]. The applied algorithms account for different signatures such as the presence and properties of prompt leptons, charged kaons and pions originating from the decay of the accompanying B meson, and assign a flavor and an associated probability. Selection requirements on the quality of the reconstructed decay vertices and the Δt measurements are applied.

The CP violation measurement is performed by maximizing the log-likelihood function

$$\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{BABAR} + \sum_j \ln \mathcal{P}_j^{\mathrm{Belle}}, \tag{2}$$

where the indices i and j denote the events reconstructed from BABAR and Belle data, respectively. The probability density function (p.d.f.) describing the Δt distribution for BABAR is defined by

$$\mathcal{P}^{BABAR} = \sum_k f_k \int \left[P_k\left(\Delta t'\right) R_k\left(\Delta t - \Delta t'\right)\right] d\left(\Delta t'\right), \tag{3}$$

and for Belle by

$$\mathcal{P}^{\mathrm{Belle}} = (1 - f_{\mathrm{ol}}) \sum_k f_k \int \left[P_k\left(\Delta t'\right) R_k\left(\Delta t - \Delta t'\right)\right] d\left(\Delta t'\right) + f_{\mathrm{ol}} P_{\mathrm{ol}}\left(\Delta t\right), \tag{4}$$

where the index k represents the signal and background p.d.f. components. The symbol P_k denotes the p.d.f. describing the proper time interval of the particular physical process, and R_k refers to the corresponding resolution function. The fractions f_k are evaluated on an event-by-event basis as a function of M_{bc}. Belle treats outlier events with large Δt using a broad Gaussian function in the p.d.f. component P_{ol} with a small fraction of $f_{\mathrm{ol}} \approx 2 \times 10^{-4}$, while BABAR includes outlier effects in the resolution function. The signal p.d.f. is constructed from the decay rate in Eq. (1), including the effect of incorrect flavor assignments and convolution with resolution functions to account for the finite vertex resolution. The models of the Δt resolution effects at BABAR and Belle follow different empirical approaches and are described in detail in Refs. [6, 31]. The background p.d.f.s for BABAR and Belle are composed of the sum of a Dirac delta function to model prompt background decays and an exponential p.d.f. for decays with effective lifetimes. The background p.d.f. is convolved with a resolution function modeled as the sum of two Gaussian functions. The background parameters are fixed to values obtained by fits to the events in the $M_{\mathrm{bc}} < 5.26$ GeV$/c^2$ sidebands.

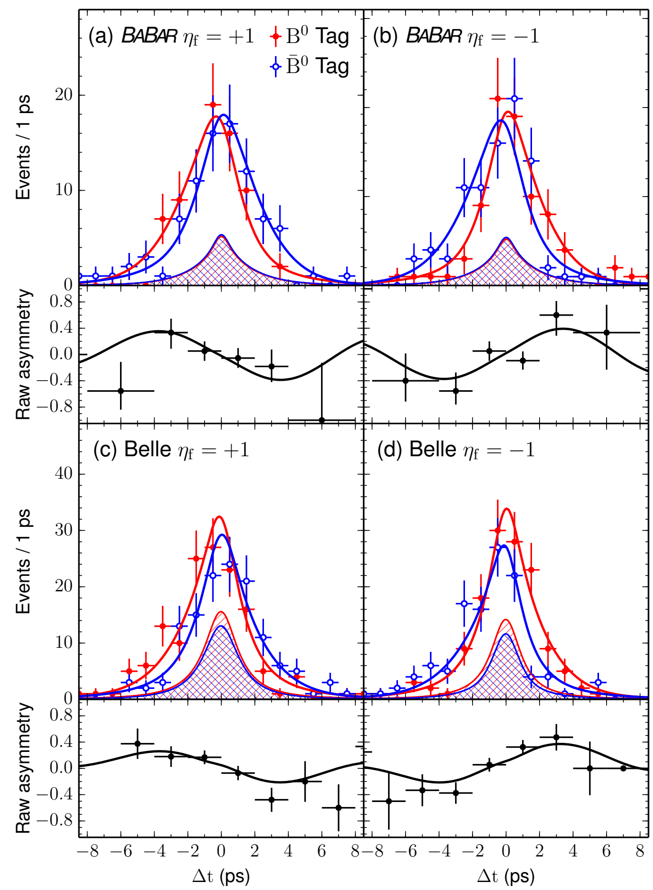

FIG. 2. (color online). The proper time interval distributions (data points with error bars) for B^0 tags (red) and $\bar{B}^0$ tags (blue) and the CP asymmetries of $\bar{B}^0 \to D_{CP}^{(*)} h^0$ decays for (a)-(b) BABAR and (c)-(d) Belle for candidates associated with high quality flavor tags. The solid lines show projections of the sum of signal and background components in the fit, while the hatched areas show only the background components.

The combined BABAR and Belle measurement is performed by maximizing Eq. (2) for events in the 5.27 GeV$/c^2 < M_{\mathrm{bc}} < 5.29$ GeV$/c^2$ signal region. The values of τ_{B^0} and Δm_d are fixed to the world averages [22]. The free parameters in the fit are $\mathcal{S}$ and $\mathcal{C}$. The result is

$$\begin{aligned} -\eta_f \mathcal{S} &= +0.66 \pm 0.10\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.}), \\ \mathcal{C} &= -0.02 \pm 0.07\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{syst.}). \end{aligned} \tag{5}$$

The linear correlation between $-\eta_f \mathcal{S}$ and $\mathcal{C}$ is -4.9%. Through comparison of the log-likelihood of the fit to the distribution from an ensemble test performed with input from the data distributions, a p-value of 0.46 is obtained. The flavor-tagged proper time interval distributions and projections of the fit are shown in Fig. 2.

The evaluation of the systematic uncertainties in the CP violation parameters follows standard approaches of the BABAR and Belle experiments described in detail in Refs. [6, 7, 33]; the results are summarized in Table II. For the vertex reconstruction, the sources of systematic uncertainties include the applied constraints and selection requirements on the vertex fits of the signal B meson and the accompanying B meson, and on the Δt fit range. These contributions are estimated by variations of the constraints and selection requirements. The systematic uncertainties due to the misalignment of the silicon vertex detectors are estimated by Monte Carlo (MC) simulations. For BABAR, the uncertainty of the z scale is estimated by variations of the z scale and corresponding uncertainties. For Belle, a possible Δt bias is estimated using MC simulations. The systematic uncertainties due to the Δt resolution functions, the parameterization of the Δt background p.d.f., the calculation of the signal purity, the flavor-tagging, and the physics parameters τ_{B^0} and Δm_d are estimated by variation of the fixed parameters within their uncertainties. Fit biases are estimated using large samples of MC-simulated signal decays. The contribution of backgrounds that have the same final states as the reconstructed $\overline{B}^0 \to D^{(*)}_{CP} h^0$ decay modes and that can peak in the $M_{\rm bc}$ signal region is estimated using D meson mass sidebands on data and using generic $B\overline{B}$ MC samples. These backgrounds account for less than 8% of the signal and consist mainly of flavor-specific decays such as partially reconstructed $B^- \to D^{(*)0}\rho^-$ decays. The systematic uncertainty due to this peaking background is estimated using MC simulations in which the peaking background is modeled, and the nominal fit procedure, which neglects this peaking background, is applied. The effect of interference between $b \to c\bar{u}d$ and $\bar{b} \to \bar{u}c\bar{d}$ decay amplitudes of the accompanying B meson is estimated using MC simulations that account for possible deviations from the time evolution described by Eq. (1) [34]. Possible correlations between BABAR and Belle are accounted for in the evaluation of the contributions due to the physics parameters, the peaking background, and the tag-side interference. In the MC studies described above, the largest deviations are assigned as systematic uncertainties. The total systematic uncertainty is the quadratic sum of all contributions.

The statistical significance of the results is estimated using a likelihood-ratio approach by computing the change in $2\ln\mathcal{L}$ when the CP violation parameters are fixed to zero. The effect of systematic uncertainties is included by convolution of the likelihood distributions. No significant direct CP violation is observed. The measurement excludes the hypothesis of no mixing-induced CP violation in $\overline{B}^0 \to D^{(*)}_{CP} h^0$ decays at a confidence level of $1 - 6.6 \times 10^{-8}$, corresponding to a significance of 5.4 standard deviations.

TABLE II. Summary of systematic uncertainties for the time-dependent CP violation measurement in $\overline{B}^0 \to D^{(*)}_{CP} h^0$ decays (in units of 10^{-2}).

Source	$\mathcal{S}$	$\mathcal{C}$
Vertex reconstruction	1.5	1.4
Δt resolution functions	2.0	0.4
Background Δt PDFs	0.4	0.1
Signal purity	0.6	0.3
Flavor-tagging	0.3	0.3
Physics parameters	0.2	< 0.1
Possible fit bias	0.6	0.8
Peaking background	4.9	0.9
Tag-side interference	0.1	1.4
Total	5.6	2.5

The analysis is validated by a variety of cross-checks. The same measurement is performed for $\overline{B}^0 \to D^{(*)0} h^0$ decays with the CKM-favored $D^0 \to K^-\pi^+$ decay mode. These decays provide a kinematically similar, high statistics control sample. The result agrees with the assumption of negligible CP violation for these decays. Measurements of the neutral B meson lifetime using the control sample and $\overline{B}^0 \to D^{(*)}_{CP} h^0$ decays yield $\tau_{B^0} = 1.518 \pm 0.026\,(\text{stat.})$ ps and $\tau_{B^0} = 1.520 \pm 0.064\,(\text{stat.})$ ps, respectively, in agreement with the world average $\tau_{B^0} = 1.519 \pm 0.005$ ps [22]. All measurements for the control sample and for $\overline{B}^0 \to D^{(*)}_{CP} h^0$ decays have also been performed for data separated by experiment and by decay mode, and yield consistent results. The results for $\overline{B}^0 \to D^{(*)}_{CP} h^0$ decays separated by experiment are $\sin(2\beta) = 0.52 \pm 0.15\,(\text{stat.})$ for BABAR and $0.83 \pm 0.15\,(\text{stat.})$ for Belle, and the results separated by the CP content of the final states are $\sin(2\beta) = 0.52 \pm 0.15\,(\text{stat.})$ for CP-even and $0.80 \pm 0.15\,(\text{stat.})$ for CP-odd.

In summary, we combine the final BABAR and Belle data samples, totaling more than $1\,\text{ab}^{-1}$ collected at the $\Upsilon(4S)$ resonance [19, 36], and perform a simultaneous analysis of the data collected by both experiments. We observe for the first time CP violation in $\overline{B}^0 \to D^{(*)}_{CP} h^0$ decays driven by mixing-induced CP violation. We measure $\sin(2\beta) = 0.66 \pm 0.10\,(\text{stat.}) \pm 0.06\,(\text{syst.})$. This result agrees within 0.2 standard deviations with the world average of $\sin(2\beta) = 0.68 \pm 0.02$ [35] measured from $b \to c\bar{c}s$ transitions, and is consistent with the measurements of $b \to s$ penguin-mediated B meson decays [9–12] at current precision. The presented measurement supersedes the previous BABAR result for $\overline{B}^0 \to D^{(*)}_{CP} h^0$ decays [15].

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